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Data for Energy Performance Analysis

Financed by The Danish Electricity Saving Trust

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1. Introduction

1.1 Background

In recent years much effort has been spend in reducing the global emission of CO2. One approach to reduce the emission is to renew the power production from being based on fossil fuels, like coal and oil, to being based on renewable energy sources, e.g. by wind turbines. This approach involves big power producing companies and politicians which have to invest money in new production methods based on renewable energy. Another approach is to lower the power consumption used both in industry and households. Especially the electricity consumed in households has been in focus in the past ten years since approximately 40 % of the personal CO2 emission is due to the power consumed in households. Many campaigns have been launched to inform consumers about how to save electricity from especially lighting and electrical products like TV's, washing machines and refrigerators. However, when it comes to heating of households many consumers find it unclear, without consulting experts, how and how much energy that can be saved. Due to the big differences between house types and heating methods in Denmark, it is hard to launch an information campaign to inform consumers about energy savings in heating of houses. However, today high frequency data for the energy consumption is very often available. This enables a possibility of using statistics and data based methods to gather information on the energy performance of a building. The high frequency data calls for a more dynamic approach, where consumers based on their own type of house can perform calculations about their energy consumption due to heating. From these calculations it could be possible to estimate the possible energy savings due to different saving strategies, e.g. additional insulation or new windows. Finally it could be possible to state the effect of the implemented strategies in annual savings. From this consumers can get a clear picture of how their actions influence their own economy. This way consumers are economical encouraged to implement the proposed methods for energy savings. For the dynamic campaign to be a success several models for the heat dynamics of different types of houses are needed. Already several models for the heat dynamics of different types of buildings have been developed, e.g. in [MNSW].

Models for the heat dynamics of a building describe the flow of energy between the inside and the outside of a building, i.e. the exchange of heat with the outside. More advanced models that describe the heat exchange between adjacent rooms can also be developed by extending already formulated models. Typically the models are formulated by using sub models for conduction, convection and radiation. Each sub model is formulated with parameters which describe the building characteristics, e.g. UA-values of windows and walls. However, these parameters can vary a lot, even between buildings described by the same model. Several methods for estimation of parameters in the model of the heat dynamics of building already exist, e.g. in [MH95]. Thus methods for getting accurate building performance data have to be developed before estimation can be conducted.

At Risø DTU an office building has been equipped with sensors for collecting data that can be used as basis for estimation of model parameters. The aim of the office building, called FlexHouse, is to act as an intelligent load to an electrical distribution system, SYSLAB, build on site of Risø. SYSLAB has been build for simulation of an intelligent energy distribution system.

1.2 SYSLAB

The energy production system of today consist of large centralized power stations using fossil fuels. These are connected in a grid that allows distribution of energy from the production plants to the consumers through a distribution network. This kind of static network only allows distribution of energy in one direction. Besides centralized power stations, the future energy production systems will consist of many small local energy producing units, e.g. wind turbines and solar panels. To be able to integrate these into the energy distribution system, a much more flexible network has to be developed. Future distributed energy systems, will allow energy to be distributed in many different directions, depending on where the energy is produced. Controlling such a system in real-time, however, is a great task and new methods are needed in order to control the flow. The two kinds of networks are depicted in Figure 1.1[1].

[1]http://ec.europa.eu/research/energy/nn/nn_rt/nn_rt_dg/article_1158_en.htm

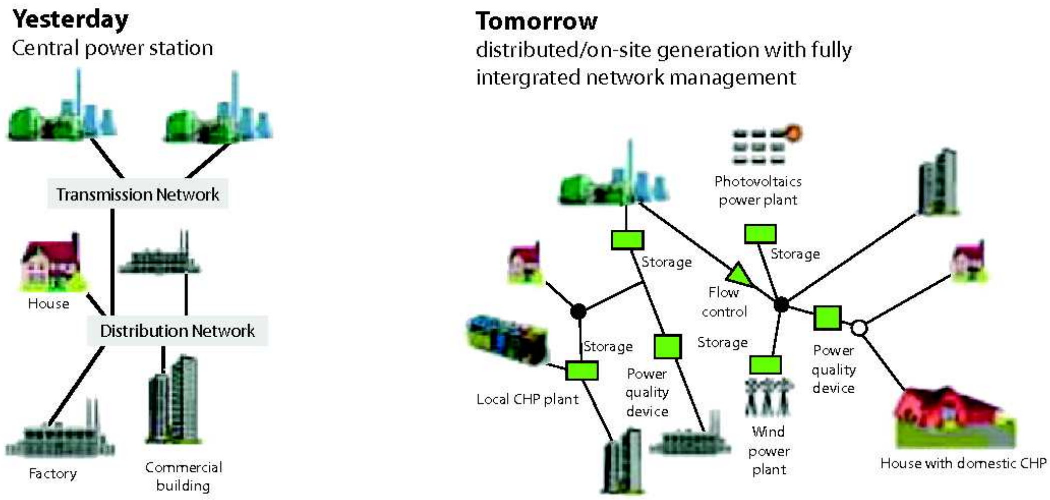

Figure 1.1: Present and future energy distribution system.

At Risø DTU, SYSLAB [2] has been build to provide an experimental platform for investigation of distributed energy systems, consisting of both power producing units and power consuming units.

The power producing units in the SYSLAB distribution network are:

- Gaia wind turbine [11 kW].
- Bonus wind turbine [55 kW].
- A vanadium battery [15 kW].
- A diesel generator [48 kW].
- A solar panel [7 kW].

where the values in brackets states the maximum energy production.

The power consuming units in the SYSLAB grid are:

- A dump load [75 kW].

[2] http://www.risoe.dk/rispubl/risnyt/risnyt2006/1_2006/SYSLAB.htm

- FlexHouse [$\approx 20\,kW$].

In the future a hybrid car will also be connected to the system. The aim is to charge the battery when excess renewable energy is available in the system but also allowing energy to flow in the opposite direction, that is, sending energy back into the network, for example to FlexHouse. In this way the battery of the car can be used as a buffer for renewable energy.

As an active player in the SYSLAB network, FlexHouse is of special interest in this project due to the possibilities for data gathering and heat control.

1.2.1 FlexHouse

FlexHouse is an office building, operating as an active load to the distributed system that SYSLAB provides. Images of the building from outside and inside are found in Appendix B. The energy supply to FlexHouse is produced by the units in the SYSLAB network and is purely electrical. One of the aims of FlexHouse is to act as an active player in the system and provide services to SYSLAB, e.g. by lowering its power consumption when the energy production is low. For this to work the SYSLAB network has to, somehow, inform FlexHouse, that the energy production is low. This can be obtained by sending a price signal to the controller. A platform for simulation of price signals has already been integrated into the SYSLAB network. If the energy produced in the SYSLAB grid is to be used optimally, space heating in FlexHouse has to take place when the renewable energy production is high, i.e. the price is low. Thus, an intelligent controller should try to minimize the total energy cost over time, but without exposing the users of the house to great fluctuations in temperature.

The load that FlexHouse provides to the energy system is due to the electrical components installed in FlexHouse. These are:

- 10 electrical space heaters [$1\,kW$].
- A refrigerator [$0.5\,kW$].
- A water heater with storage tank [$4\,kW$].
- A coffee machine [$2\,kW$].
- Five air-conditioners [$1\,kW$].

The size of FlexHouse is approximately $125\,m^2$ divided between eight rooms and a toilet. The rooms have been numbered 0 to 7 to distinguish between them. A layout of FlexHouse can be seen in Figure 1.2 where also the room numbers are shown. Room 1–7 have been arranged as small offices (see the image in Figure B.8),

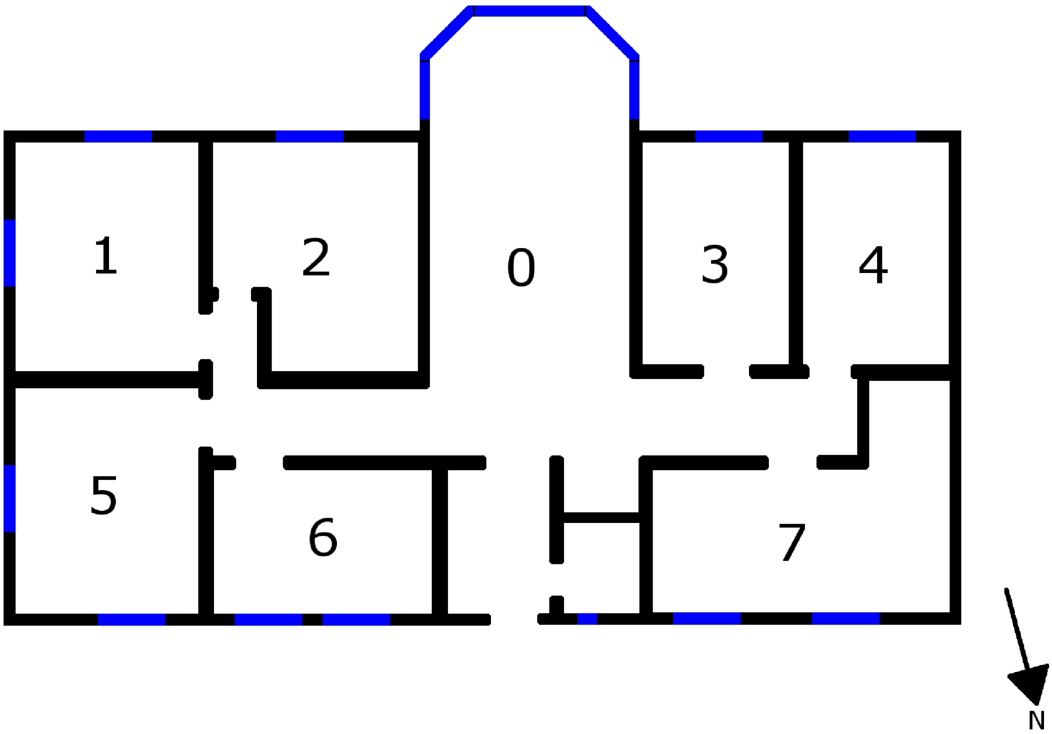

Figure 1.2: FlexHouse layout

each with a desk, office chair and a computer. The main room, room 0 (see Figure B.5), has been furnished with tables and chairs to accommodate meetings. Moreover room 0 contains a small kitchen with a refrigerator and a coffee machine (see Figure B.6). The southern wall in the main room is dominated by a large window facade. From the main room access to a toilet is possible, where the water heater is placed. The five air-conditioners are mounted in the five rooms facing south, i.e. room 0–4. Electrical space heaters are mounted in room 1–6, whereas room 0 and 7 each has two heaters mounted. With the present hardware, however, it is not possible to measure the heat input from the air-conditioners. It is therefore assumed that these are turned off during measurements of the energy consumption in FlexHouse.

Even though FlexHouse is arranged as an office building, the building is only used approximately once a week by student helpers working on the controlling software running on a server in room 0.

1.3 Problem Formulation

The aim of this report is to describe a method for collecting building performance data for estimation of parameters in models for the heat dynamics of buildings. The emphasis will be put on how data was collected during six different experiments conducted in FlexHouse during February and March 2008.

1.4 Outline

In Chapter 2 the possibilities of gathering data in FlexHouse is described along with a description of how the data was gathered. Chapter 2 also contains a description of how the electrical space heaters in FlexHouse can be controlled. An optimal strategy for controlling heat input by use of PRBS-signals is also explained in this chapter. In Chapter 3 the data from four successful experiments is verified, e.g. by several plots of the gathered data. At last, in Chapter 4, possible future experiments are stated.

2. Data

Several experiments were conducted in FlexHouse during the period from February 13th 2008 to April 1st 2008. Unfortunately some of the experiments failed due to hardware problems, but four experiments were conducted without any significant problems. The purpose of the experiments were to generate building performance data, that can be used to estimate the building performance parameters in a model for the heat dynamics of FlexHouse.

The first section in this chapter describes the software that was developed during this project. The main purpose of the software has been to control the heat input from the heaters and to store measurements. Section 2.2 describes the hardware in FlexHouse. In Section 2.3 it is described how the data were collected and in Section 2.4 Pseudo-Random Binary Sequence signals (PRBS) are explained. This is used in Section 2.5 to design the heat input from the electrical heaters for six different experiments conducted in FlexHouse.

2.1 FlexHouse Software

Two applications were developed during this project. The purpose of the first application, JavaPowerFlexHouse, is to control the states of FlexHouse and to store measurements from the inner part of FlexHouse. The second application, WeatherStation, is used to get measurements from the outdoor environment. Both applications were developed in Java.

2.1.1 JavaPowerFlexHouse

In cooperation with Francesco Sottini, who is employeed as a student helper at Risø DTU, the application, JavaPowerFlexHouse (JPFH), was developed to control the heating and lighting in each room in FlexHouse. The application communicates through a LabVIEW application to sensors and actuators placed around in FlexHouse.

The first version of JPFH had a simple heating controller implemented, which turned on the heaters if the temperature in a room dropped below a defined threshold. The second version added support for synchronous control of heaters through predefined PRBS-signals (Section 2.4). This version also added support for storing measurements in a log-file on the server. Notice that this decouples any feedback from the room temperature. The second version of JPFH showed to be very unstable due to the LabVIEW application having problems in processing the messages to the actuators and from the sensors. This resulted in large lags up to an hour and after some time the application would stop. In the third version some corrections were made to the LabVIEW application and the number of messages sent from JPFH were reduced. This increased stability and solved the problem with the large lags in communication. The system, however, still showed some instabilities due to hardware problems. This resulted in some of the experiments stopped earliere than planned. Unfortunately the hardware could not be replaced and some of the measurements are therefore affected by this. The latest version of JPFH still only allows the heaters to be synchronously controlled, therefore only one PRBS-signal is used to control all the heaters. The main reason why single heater control was not implemented was primarily due to the limitation of messages being processed by the hardware.

2.1.2 WeatherData

To be able to measure and store external data a weather station has been raised on the east side of FlexHouse. The data from the weather station is sent through a telephone line (RS-232) to the server in the main room. The WeatherData application interprets an incoming bit stream and extracts the needed data. When the measurements have been extracted, the data is passed on to JPFH that handles the logging of the measurements on the server.

Source code from WeatherData.java can be found in Appendix C.

2.2 FlexHouse Hardware

The hardware installed in FlexHouse enables the temperature state of each room to be monitored and controlled. The central point in the system is JPFH, that runs on the server placed in the main room of FlexHouse. From the application it is possible to communicate wirelessly with the various sensors and actuators placed around in FlexHouse. A layout of FlexHouse can be seen in Figure 2.1, where heat sensors, electrical heaters and windows are marked.

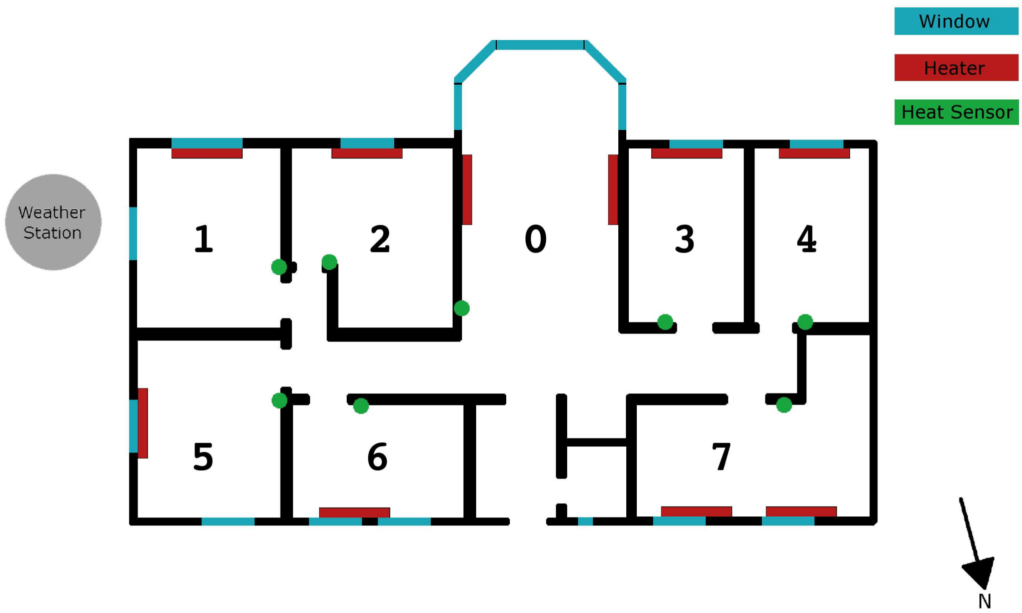

Figure 2.1: FlexHouse layout.

The following sections first describe the sensors which monitors the temperature states and secondly the actuators that are used to control the state of each room.

2.2.1 Hardware for Measurements

Several types of sensors have been installed in FlexHouse which communicates wirelessly with the server in FlexHouse. Each room, except the toilet, contains the following sensors.

- Temperature Sensor

- Door Sensor
- Window Sensor
- Motion Sensor
- Light switches

A temperature sensor is mounted in each room, these play a key role in this project by monitoring the indoor temperature state, i.e. T_i, in FlexHouse. The sensors are of the type EnOcean SR-04 and are mainly driven by small solar panels build into the sensors. In lack of light, power is provided by a battery. The temperature sensors have a resolution of $0.15\,K$ and an accuracy of $0.5\,K$. The temperature cannot be read directly from the sensors but the measured temperature is transmitted regularly to the server. According to the datasheet for the sensors[1] temperature measurements should be transmitted every 100th second if changes are more than $0.8\,K$ and every 1000th second otherwise. However, during the periods of measurements the heat sensors sometimes failed to meet this requirement, and at some occasions having up to about an hour between transmissions. An example of the performance of the temperature sensors is seen in Figure 2.2.

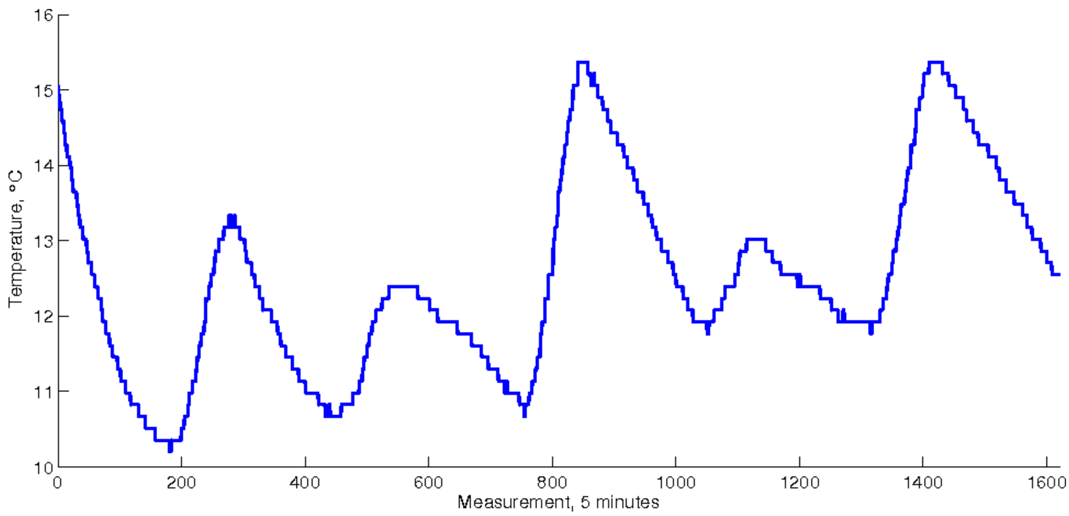

Figure 2.2: Temperature measurements from a temperature sensor.

A motion sensor has been mounted in each room and if a person is present a signal is sent to the server. For each measuring interval JPFH logs if a person has been

[1] http://www.thermokon.de/downloads/service/44/Produktblatt_SR04_10.pdf

present.

Every door and window in FlexHouse has a sensor attached. As with the motion sensors it is logged for each interval if a door or a window has been open.

Light switches are simply used to turn the light on and off. When a switch is hit JPFH is notified, which then tells the light actuator to change the state of the light source. The data from the switch sensors is not stored neither could it be used to improve a heat transfer model. The data from the switches could be used in conjunction with the motion sensors to turn off the light if no one is present.

2.2.2 Weather Data

As described in Section 2.1.2, weather data were collected directly from outside FlexHouse. The local weather data ensures optimal condition for measuring the input data to a heat transfer model. Following weather data can be measured from the weather station

- Global radiation
- Outdoor (ambient) temperature
- Wind speed
- Wind direction

The weather station is placed $4\,m$ above ground which is not the official standard way to measure weather data. However, because local data is prioritised and to get clear of buildings the measurements from the weather station are assumed to be a good approximation to standard data. Unlike the temperature sensors, measurements from the weather station could be read at any time and showed no deviation from what is expected. Figure 2.3 shows a series of weather measurements from a day in February.

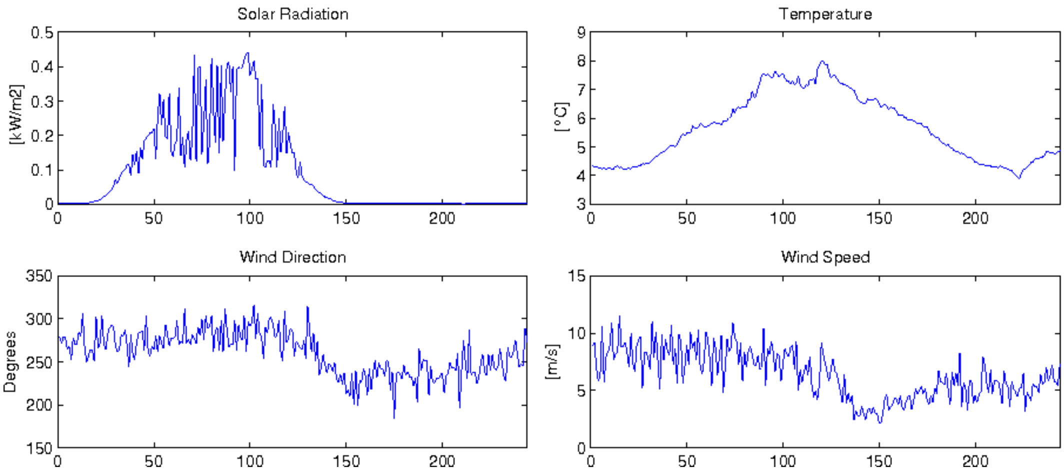

Figure 2.3: Weather data from February 28th 2008.

2.2.3 Controlling Hardware

Actuators have been installed for most light and heat sources in FlexHouse. As stated in Section 2.2.1, the light actuators cannot improve a heat transfer model. The actuators for the heaters, however, are of great importance since the heat input from the space heaters is the only part of the input to a model of the heat dynamics, that can be controlled. The actuators for the space heaters are controlled from JPFH and hence support for control by PRBS-signals was implemented here.

The heaters are powered by electricity, which makes it easy to control the heat input very precisely compared to hot water systems. The specification for the heaters states the effect to be $1.0\,kW$. This was verified by measuring the current flow to a heater. Here the current was found to be $I = 4.6\,A$. Assuming the heater acts as a linear resistor, the effect is given by $P = UI = 220\,V \cdot 4.6\,A = 1012W$, which is consistent with the specification. In the following it is assumed that the effect of each heater is $1.0\,kW$.

2.3 Data

Six experiments were conducted in FlexHouse during the period from February 13th 2008 to April 1st 2008. Due to uncertainties in measurement time, the data from the two first experiments have been discarded. Data from the following four experiments are acceptable, and only the last experiment stopped too early due to application failure. Plots showing the entire data from the four experiments are showed in Appendix A For all experiments a sampling interval of 5 minutes have been used. A typical series of measurements can be seen in Figure 2.4

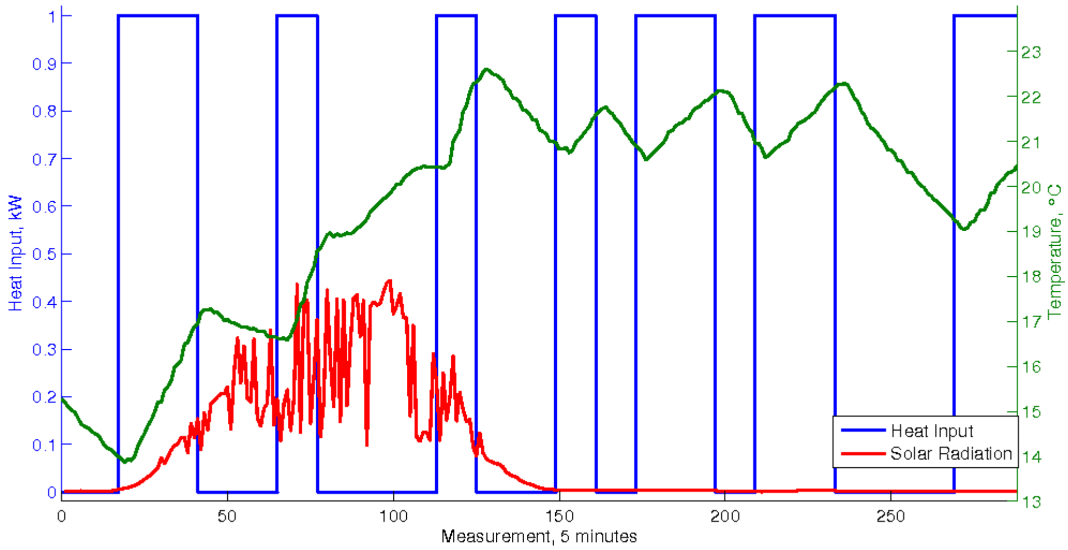

Figure 2.4: Temperature, heat- and radiation input from February 28th 2008

From the figure it can be seen that the air temperature shows a time delay of approximately 20 minutes to heat input. That effect is probably due to the time it takes for the heat to propergate through the indoor air to the temperature sensors. From the figure it is also seen that there is a great variation in the measured global radiation. This effect is due to the variation in the cloud cover. Moreover the effect from solar radiation can clearly be seen between measurement 75 to 120, where the temperature in FlexHouse rises even though the heaters are turned off.

All measurements were written as comma-separated values in a log-file on the server. The log-file is a normal text file containing ASCII characters. The logging was set to be every 5 minutes, but due to limited processing time on the server this interval had some variation, see Appendix A. For each logging it was checked for each room, if a new temperature reading had been received. If so the new temperature measurement was saved with a timestamp in the log-file, otherwise the last received measurement was saved instead. The states of the motion-, window- and door-sensors were also saved in the log file. When all the measurements from FlexHouse had been logged, values from the weather station were collected and written to the log-file as well.

A typical output from a data file can be seen in Appendix D.

2.4 PRBS - Pseudo Random Binary Sequence

The input from the heaters is very important since it is the only input that can be controlled. It is therefore crucial that the signal controlling the heat input is designed such that optimal conditions for estimation of the system parameters are achieved. A widely used method in the time domain is to use PRBS-signals, which is a deterministic signal with white-noise properties. Moreover PRBS-signals show no correlation with other external signals, e.g. weather data. The signal shifts between two levels and may only switch from one level to the other at time $t = 0, \lambda, 2\lambda, \ldots,$ where λ is the clock period or the basic period of the signal. The strength of PRBS-signals is that the signal is deterministic, therefore the signal can be designed before an experiment; also the experiments are repeatable. PRBS-signals are periodic with period $T_0 = N\lambda$, where N is an odd integer. An example of a PRBS-signal with $N = 63$ and $\lambda = 2$, and the corresponding autocorrelation function can be seen in Figure 2.5.

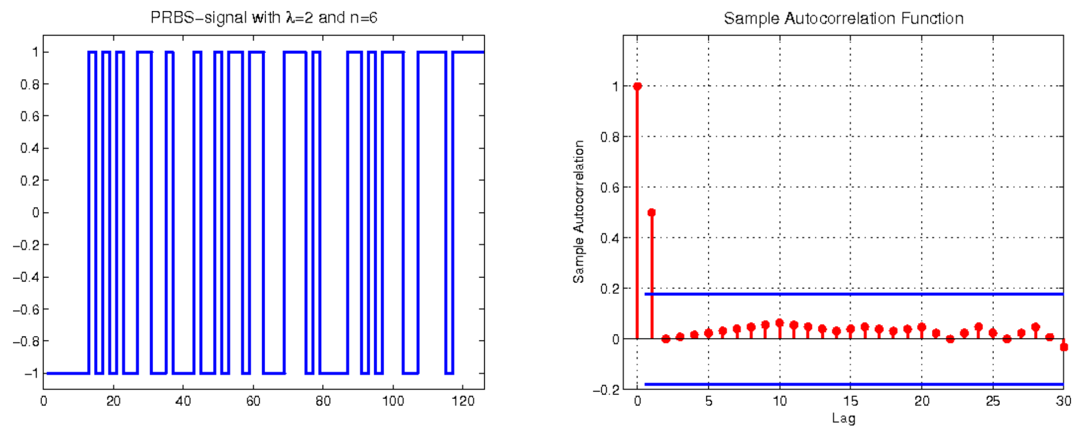

Figure 2.5: PRBS-signal and corresponding autocorrelation function.

One way to generate PRBS-signals is based on the maximum-length sequence for which $N = 2^n - 1$, where n is an integer. For a full description see [God80]. The longest interval in the sequence where the signal is either on or off is givenby $n\lambda$.

PRBS-signals have been chosen to control the space heaters in FlexHouse, due to the properties of the signal, moreover the signal corresponds well with the electrical space heaters in FlexHouse, since these easily can be controlled by a binary signal.

This implies that all traditional feedback is deactivated.

2.5 Experimental Design

The design of the heat input signal is very important if good estimates are to be achieved. Therefore the signal should be designed such that the system is excited at frequencies where the time constants are located. The estimation of time constants for the model of the heat dynamics of FlexHouse is based on the results found in [MS] and [MNSW], where the short and long time constant were found to be $\tau_1 = 26$ minutes and $\tau_2 = 154$ hours respectively. However, these results are for a test cell which is extremely airtight and well insulated. For an old house, like FlexHouse, the time constants of the inner and outer walls can be assumed to be much smaller. Therefore the short time constant is expected to be around 30 minutes and the long time constants to be around 50 hours.

To excite the system in the area of the small time constant, λ should be chosen to be around 30 minutes. To excite the system in the area of the long time constants, $n\lambda$, i.e. the longest interval where the signal is either on or off, should be chosen to be around 50 hours. Unfortunately, due to the usage of FlexHouse, only 6 consecutive days of measurements are possible if noise from people is to be avoided. This restricts the PRBS-signal to be less than 150 hours and it has therefore been chosen to lower $n\lambda$ to be either 12 and 24 hours, when designing the heat input. Table 2.1 shows the design parameters for each experiment conducted in FlexHouse.

Experiment	Measurement id.	n	λ	N	$n\lambda$	$T_0 = N\lambda$	Heaters
1	080201	6	2 h	63	12 h	126 h	10
2	080206	6	2 h	63	12 h	126 h	10
3	080213	6	2 h	63	12 h	126 h	10
4	080227	6	2 h	63	12 h	126 h	7
5	080305	6	4 h	63	24 h	252 h	2
6	080326	6	20 m	63	2 h	21 h	7
		5	3 h	31	15 h	93 h	7

Table 2.1: Design parameters for PRBS-signals for measurements in FlexHouse

In the first two experiments all ten space heaters were controlled with the designed PRBS-signal. However, due to problems with the wireless communication the measurements collected were discarded for both experiments. The communication problems caused large time lags between the messages being send to the space heaters.

Information about time during measurements was therefore lost, since it was not known when an actuator had received a message and had turned on the heater. Furthermore JPFH stopped after a few days due to messages piling up in the system. Further development in the controlling software solved this problem and the time lags for messages in following experiments were significantly reduced. Unfortunately the system still showed some instabilities and shut down during experiment 1 and 2. The data from these two experiments was therefore discarded.

The aim of the third experiment was a compromise between exciting the system in the area of the small- and large time constants. However, the ten heaters produced too much heat, such that the temperature rose to more than 30 $^\circ C$, causing an internal switch to turn off some of the heaters. Therefore the actual heat input from the heaters was not known in periods with more than 30 $^\circ C$. This can be seen in Figure 2.6, where the indoor temperature decreases from measurements 1400–1500 even though the heater signal is on. Further note that the indoor temperature is decreasing slower when the heater signal is still on, measurements 1400–1500, than when the heater signal has turned off, measurements above 1500, indicating that only some of the heaters have turned off due to the internal switch.

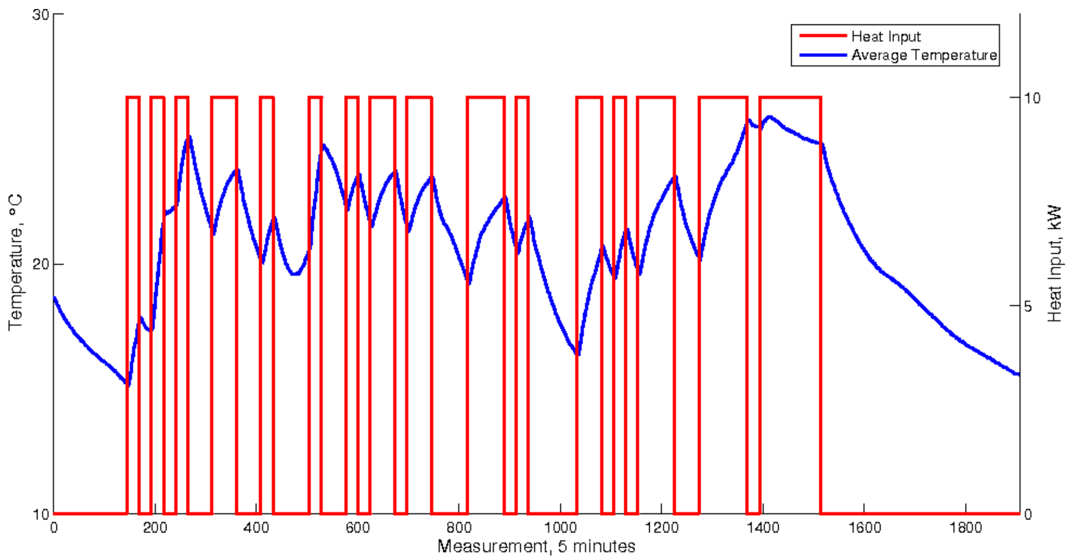

Figure 2.6: Heat input and average temperature for measurement 080213.

For the third experiment, data up to measurement 1350, i.e. the first 113 hours, should be used for estimation of parameters in a heat transfer model, whereas the following measurements should be discarded.

To reduce the heat input the number of heaters were reduced to seven heaters in the fourth experiment. These were controlled by the same PRBS-signal as in experiment three. Room two and three were selected not to have any heat input due to the large surface area towards inside of the building, furthermore the second heater in room 7 was also turned off. This ensures that the heat is distributed more evenly throughout the house. Measurements from the fourth experiment produced good results and have been used for parameter estimation.

The fifth experiment was designed to excite the system in the area of the large time constant, therefore a long clock period was chosen. To avoid that the temperature rose to more than $30\,^{\circ}C$, only two heaters were chosen to give heat input. To ensure an even distribution of heat, the heaters in room two and three were chosen to produce the heat input. The PRBS-signal was too long to fit within the six days measurement period and after the sixth day the measurements were stopped. Measurement from the six days, however, showed good results and can be used for estimation of unknown parameters in a model of the heat dynamics in FlexHouse.

The sixth experiment was designed with two PRBS-signal; the first signal was designed to establish stationarity before the second PRBS signal, which was designed to excite the system around the large time constants. The same seven heaters as in the fourth experiment were selected to produce heat input, due to the good results from the fourth experiment. Unfortunately the system shut down after the third day and the following measurements were lost. Measurements from the first three days can be used.

To reduce unknown heat input the refrigerator and water heater were turned off during all experiments. PRBS-signals used for control of the heaters in FlexHouse, have been generated using MATLABs `idinput`-function, which generates a PRBS-signal, given input for N, λ and levels.

3. Data Validation

This chapter uses an empirical approach to validate the data collected in FlexHouse. For the successful data series collected in experiment 3, defined in Table 2.1, the data is plotted and commented. Plots af the complete data from experiment 3,4,5 and 6 are showed in Appendix A

3.1 Experiment 3

From Figure 3.1 the variation of global radiation over the day is clearly seen. The six peaks are due to the motion of the sun during the six day period. Moreover time period where the incident radiation is positive can be seen to be approximately 120 points, which is equivalent to 10 hours. This agrees well with what could be expected of a normal day in February.

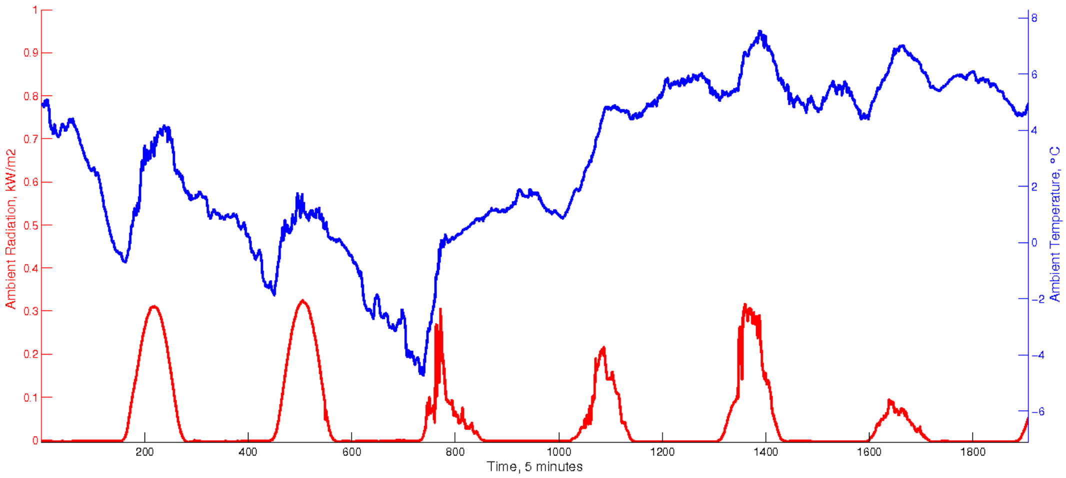

Figure 3.1: Weather data collected from 13th February to 20th February 2008.

From the figure is also seen that the incident radiation peaks with a maximum at approximately 350 Wh/m2, which means that even for a cold winter day, solar radiation can have a big impact on the energy flow into buildings if windows are present. The outdoor temperature is seen to vary with the solar radiation, i.e. the temperature raises when after sunrise. This dependency is consistent with what could be expected in the outdoor temperature signal.

Figure 3.2 shows the heat input data that was logged on the server in the main room during the period of the third experiment. The heat input follows exactly the PRBS-signal that was implemented in JPFH. This shows that the implemented software is capable of controlling the electric space heaters in FlexHouse.

Figure 3.3 shows the measured temperature in room 0—7 during the third experiment with their mean temperature highlighted. It is seen that the room temperatures follow the mean temperate nicely with an approximately constant interval between the lowest and the highest room temperature. The differences in indoor temperature are due to the air infiltration, cooling of the outer walls due to wind and window area in each room. Each room temperature, however, is seen to vary nicely without any rapid or unexpected changes. This suggest that the temperatures are accurate and could be used for estimation of parameters in a model of heat flow between the rooms in FlexHouse.

In Figure 4 the mean room temperature is plotted along with the heat input. The variations in temperature are clearly seen to be affected by the heat input. When

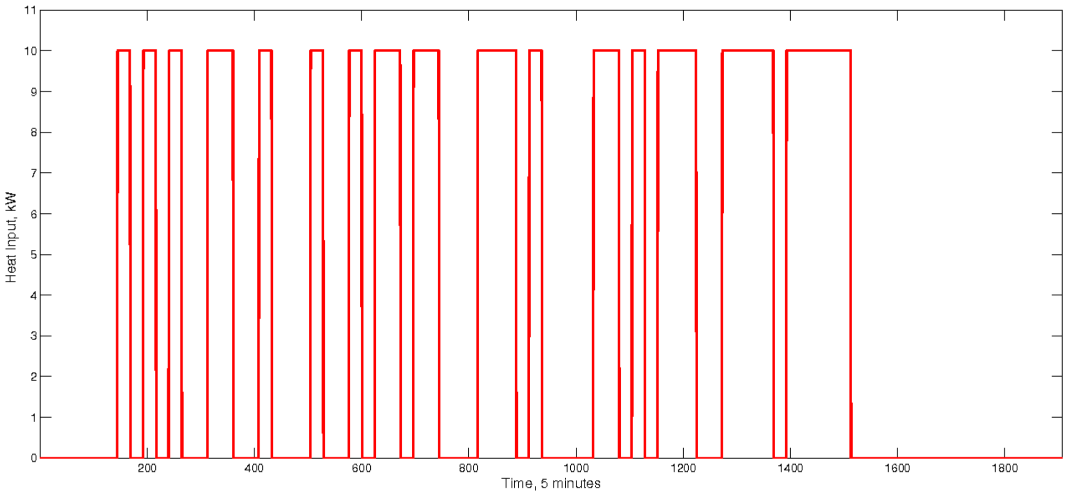

Figure 3.2: Heat input into FlexHouse from 13th February to 20th February 2008.

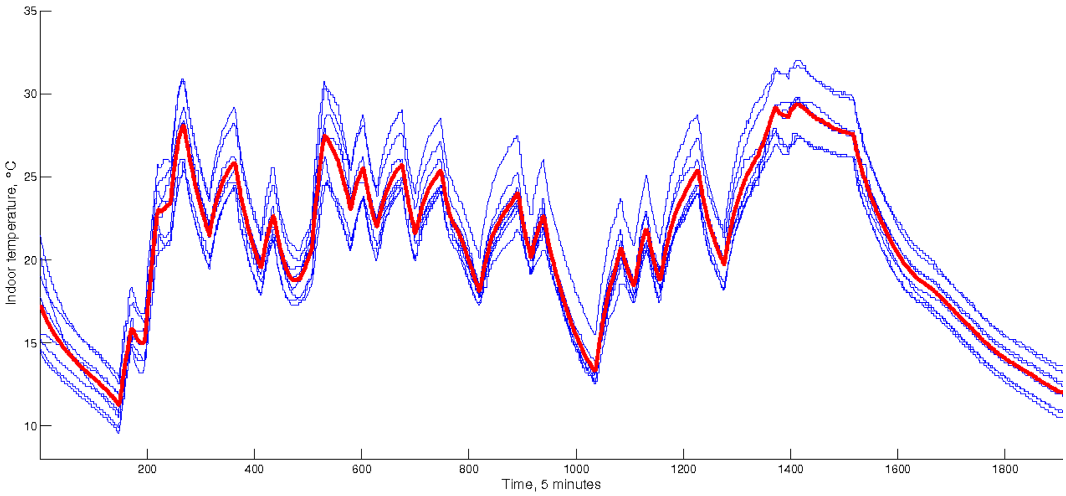

Figure 3.3: Measured room temperatures in room 0–7 with the mean temperature highlighted

the electrical space heaters are turned on the temperature rises and when they are turned off the temperature drops due to the lower outside temperature. Due to the good properties of the PRBS-signal, this data series can be used to find good estimates of the building parameters of FlexHouse. Also the effect of solar radiation can be seen around measurement 450, where the indoor temperature raises even though the heaters are turned off.

This chapter shows that it is possible to log several states of FlexHouse using wire-

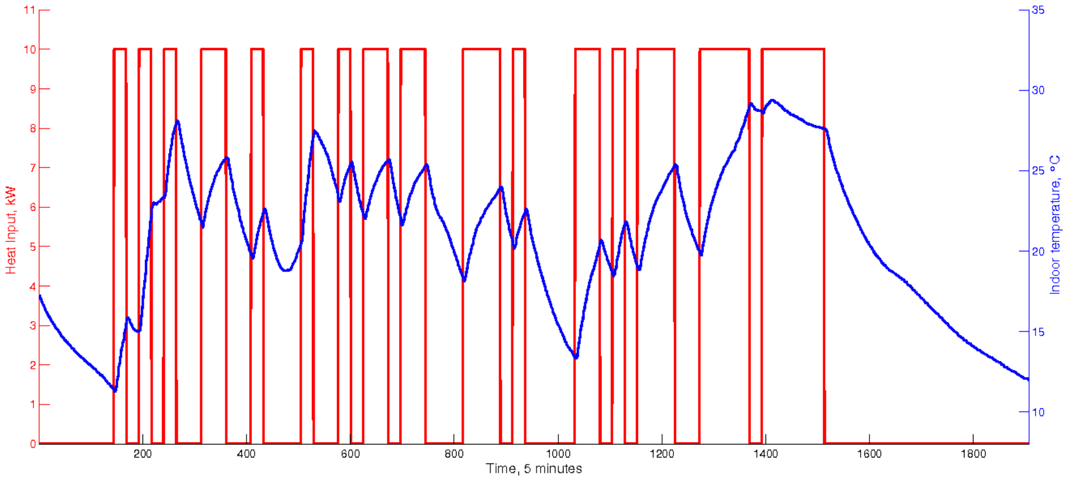

Figure 3.4: Heat input and mean temperature in FlexHouse from 13th February to 20th February 2008.

less sensors and that the logged building performance data is accurate enough to estimation of parameters in a model for the heat dynamics of FlexHouse.

4. Possible Future Work

First of all, future work should derive the models for the heat dynamics of different types of residential houses. These models should be sufficient to describe the heat flow in the most common types of houses in Denmark, if they should be used in a national campaign.

As indicated in Chapter 2 many problems were associated with collecting building performance data in FlexHouse. Future work should search for solutions to overcome these problems if estimation of building parameters is to be a success. Future work should strive to increase the performance of the temperature sensors. Better performance is essential if accurate estimates of the building parameters are to be achieved. Placing the temperature sensors at new locations could possibly decrease the time between transmissions if better lighting or transmission conditions can be found. The sensors, however, must not be placed in direct sunlight which could compromise the temperature measurements. Also the batteries in the heat sensors could be changed more often. As an alternative to the wireless temperature sensors wired sensors should be considered. This would greatly increase accuracy and reliability.

Due to the synchronized control of heaters it is not possible to give any precise estimates of the heat flow between rooms. Thus software for better control of heaters should be implemented if parameters for the heat flow between rooms are to be estimated. Further development in controlling software could implement non-synchronous control of the heaters in FlexHouse. This kind of control would, however, require hardware that is capable to handle more messages being sent. A new approach could be to implement control by wired actuators. This, however, would require further investments in hardware. Besides better hardware performance more data is needed if good estimates should be found. This can be achieved by conducting more experiments in FlexHouse, if possible with longer periods of measurements. Longer periods of measurements would also make it possible to design heat input by

PRBS-signals with a longer clock period. Especially new experiments should be conducted with heat input designed with the purpose of identifying the time constant of the inner walls. As in the sixth experiment the PRBS-signal should composed by two signals, where the purpose of the first signal is to achieve stationarity before the second signal. Experiments could also be conducted where some of the input parameters have been eliminated. For example the windows could be blocked to avoid input from solar radiation.

At last experiments should be carried out in various types of residential houses. This way building performance data can be use to verify that a given model can be used to describe the heat flow. Also experiments should be conducted in houses build of different materials, e.g. bricks, concrete or wood. Also heat flow in flats should be investigated.

A. Plots of data from experiment 4,5,6 and 7

For each of the four successful experiments all recorded observations are showed with the following plots:

- The time difference between each iteration of the JavaPowerFlexHouse application
$$\Delta time_i = time_i - time_{i-1} \tag{A.1}$$
where $time_i$ is the time where the i'th iteration was runned. Optimally this difference should be exactly 5 minutes, but due to the application being runned on a multi-threaded computer, other processes sometimes occupied the processor and thereby introduced varying delays before an iteration in the application was runned.
- The PRBS heater signals for each heater in Flexhouse.
- The temperature in each room in Flexhouse.
- The outdoor temperature measured at the local weather station (section 2.2.2).
- The global radiation measured at the local weather station.
- The wind speed measured at the local weather station.
- The wind direction measured at the local weather station. North is 0 degrees.

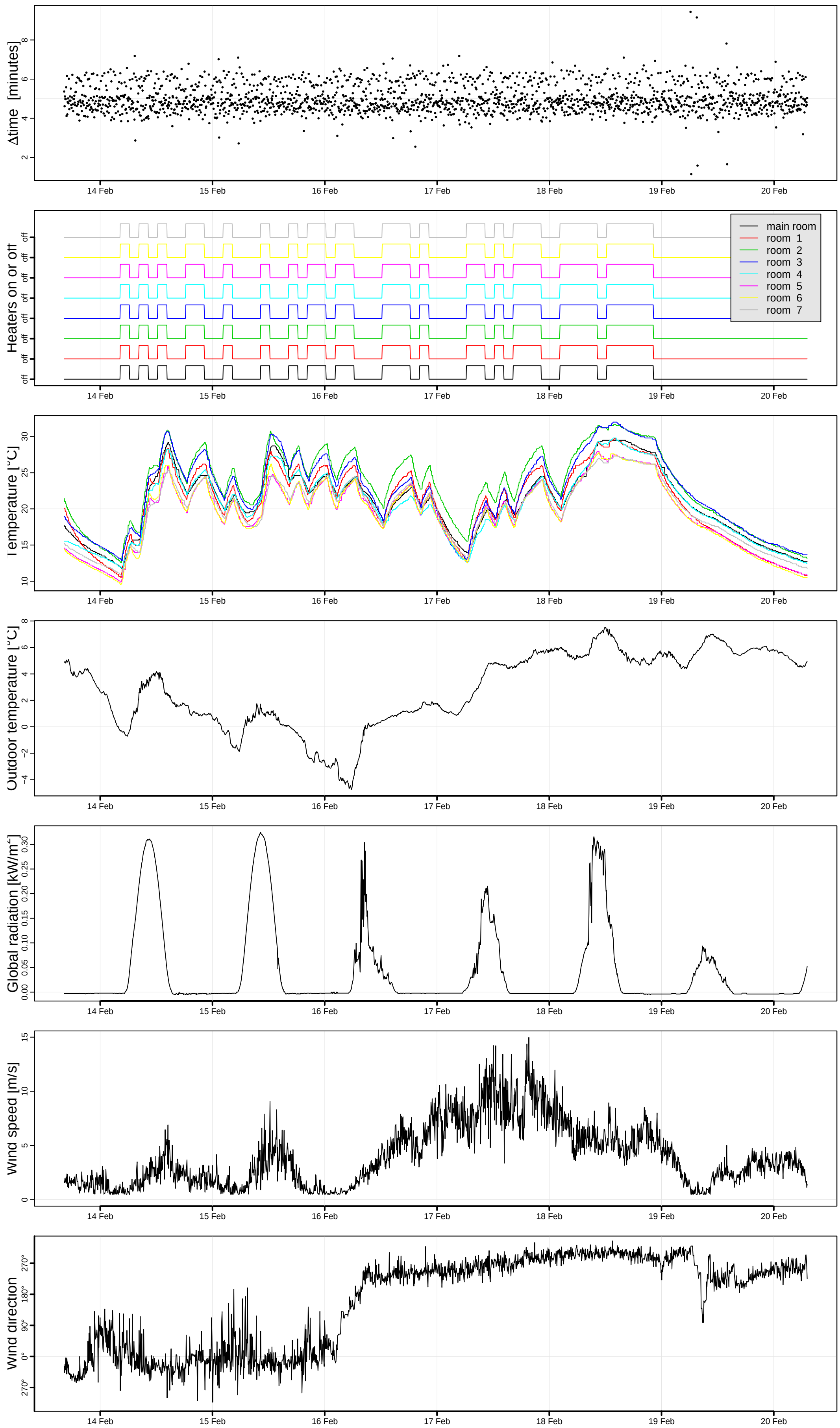

Figure A.1: Data from experiment 3

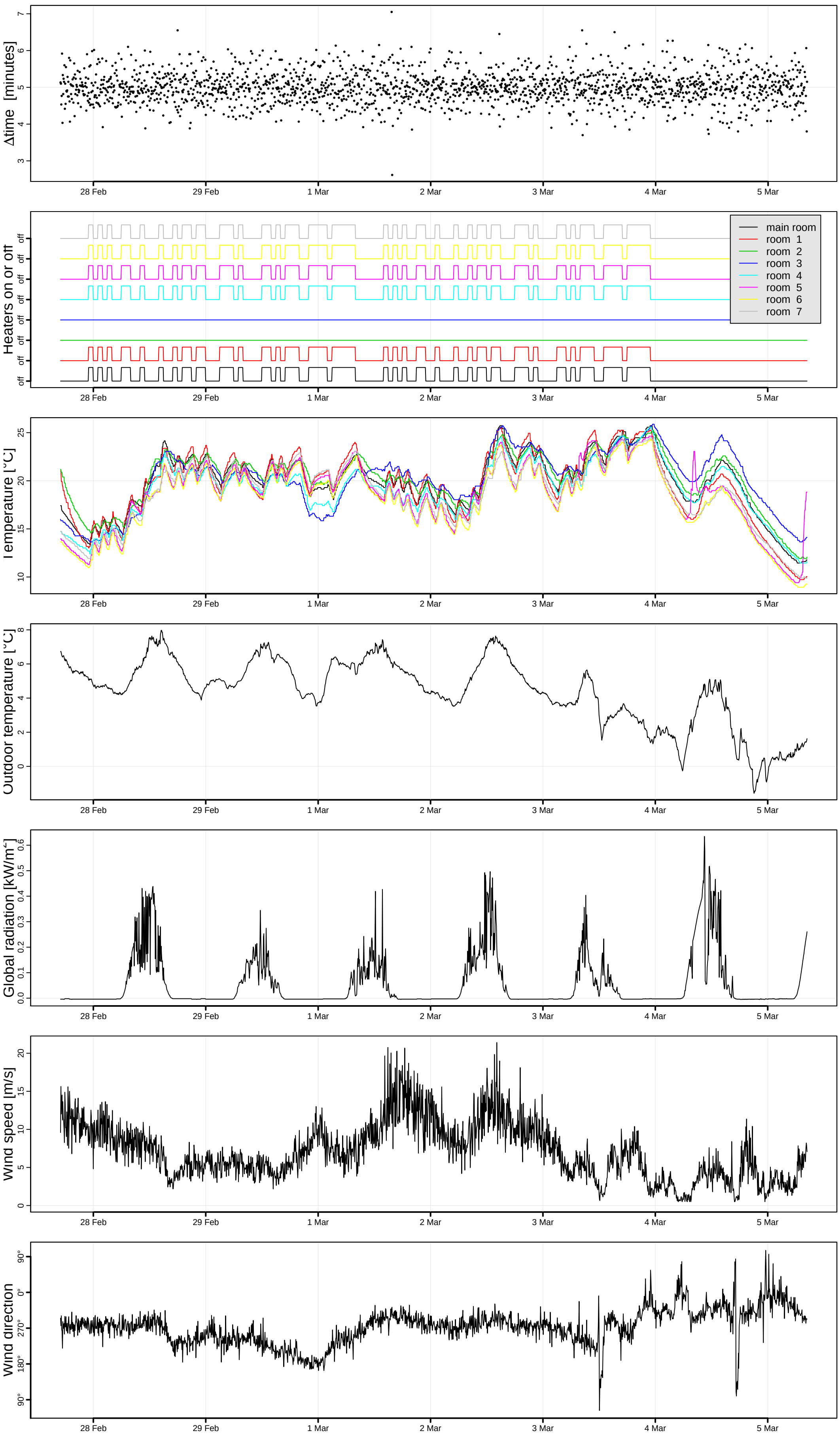

Figure A.2: Data from experiment 4

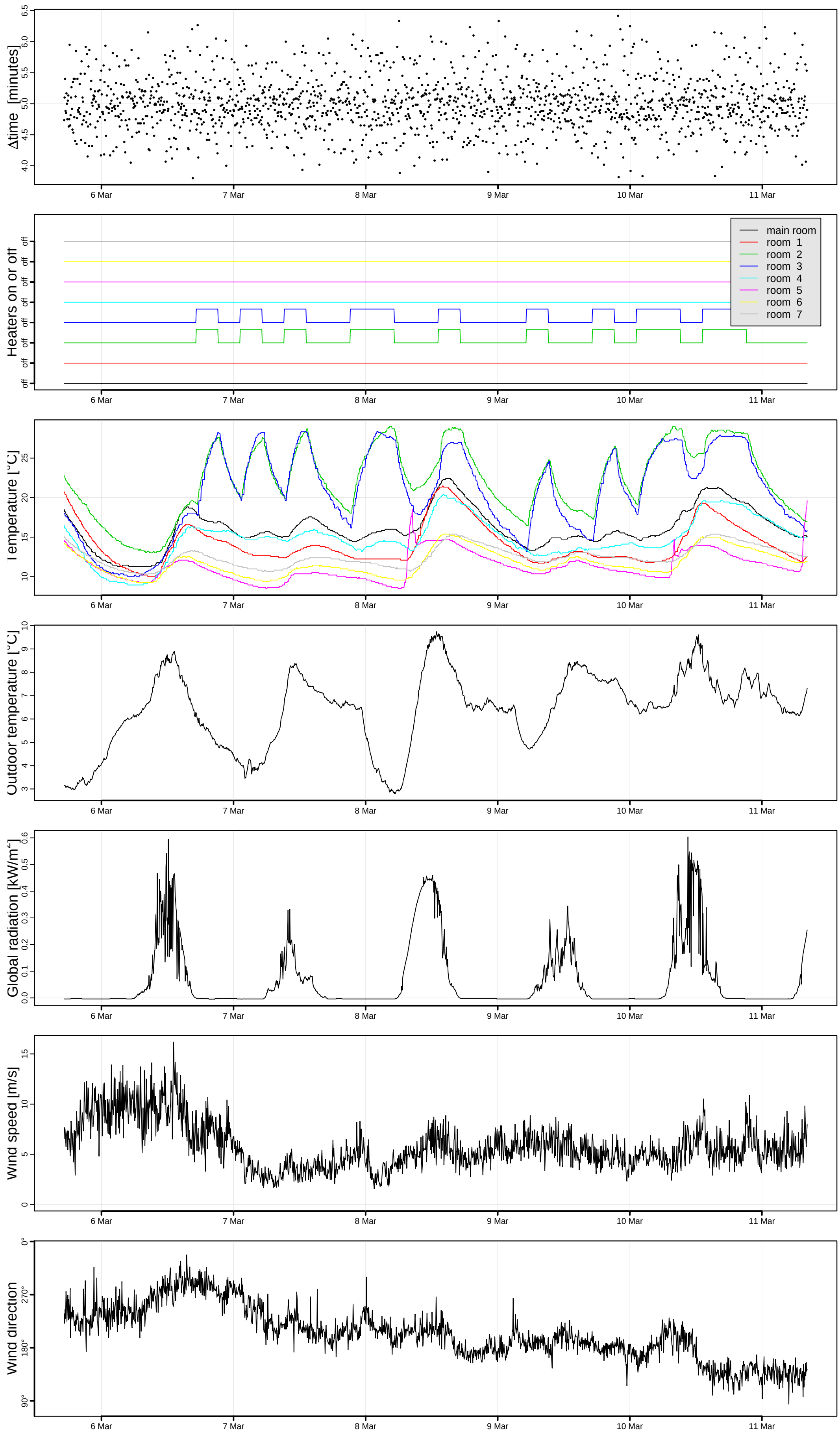

Figure A.3: Data from experiment 5

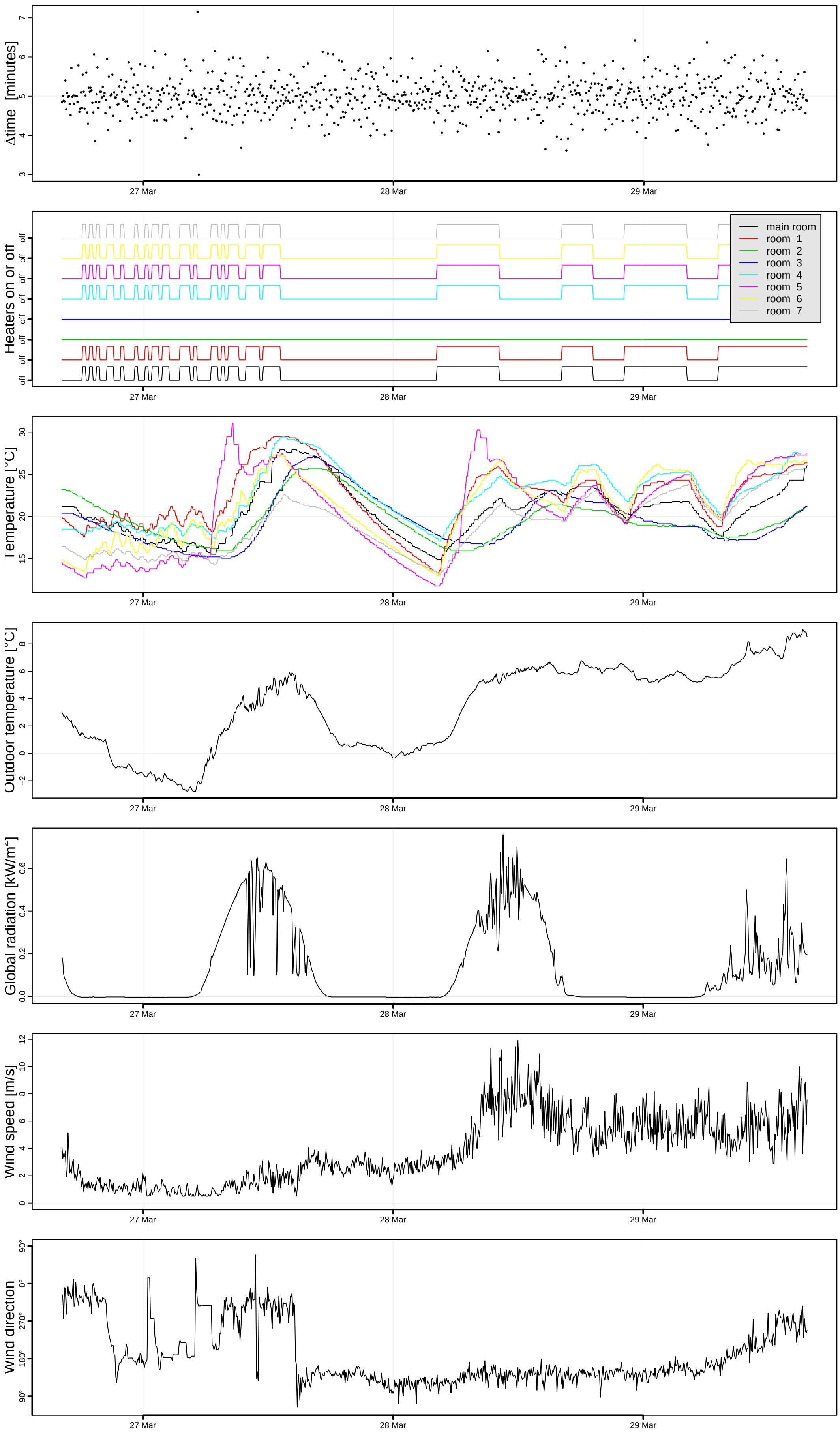

Figure A.4: Data from experiment 6

B. Images of FlexHouse

Images of FlexHouse are found in this chapter. The caption of each image explain the content of the image.

Figure B.1: The east facade.

Figure B.2: The south facade.

Figure B.3: The west facade.

Figure B.4: The north facade.

Figure B.5: The main room or Room 0.

Figure B.6: The kitchen in the main room.

Figure B.7: The server hardware.

Figure B.8: Room 2. The interior consisting of a desk and some few other items, are similar in all rooms.

Figure B.9: Window in the ceiling.

Figure B.10: The air gab between the house and the ground.

C. Application Source Code

Listing C.1: WeatherData.java

```java
package management;

public class WindStationData {

        private static int DIVISION_FACTOR = 2;
        private static int CLOCK_FREQUENCY = 16000;

        private float a1_radiation;
        private float a23_windWane;
        private float a4_humidity;
        private float a5_temperature;
        private float d1_windSpeed;
        private String timeStamp;

        public WindStationData(int a1, int a2, int a3, int a4, int a5, int d1){
                this(a1, a2, a3, a4, a5, d1, new java.util.Date().toString());
        }

        public WindStationData(int a1, int a2, int a3, int a4, int a5, int d1, String time){
                this.a1_radiation = toInputVoltage(a1)*6.3291f;
                this.a23_windWane = 356.5f*toInputVoltage(a2)/toInputVoltage(a3);
                this.a4_humidity = toInputVoltage(a4);
                this.a5_temperature = 100.f*toInputVoltage(a5)-40.f;
                this.d1_windSpeed = 0.63390f*toInputFrequency(d1)+0.18914f;
                this.timeStamp = time;
        }

        public float getRadiation(){
                return this.a1_radiation;
        }

        public float getWindDirection(){
                return this.a23_windWane;
        }

        public float getHumidity(){
                return this.a4_humidity;
        }

        public float getTemperature(){
                return this.a5_temperature;
        }

        public float getWinSpeed(){
                return this.d1_windSpeed;
        }

        public String toString(){
                return new String("Record Time: \t" + timeStamp +
                                        "\nRadiation: \t" + a1_radiation + " kW/m2"+
                                        "\nWind: \t\t" + a23_windWane + " degrees" +
                                        "\nHumidity: \t" + a4_humidity + " %RH"+
                                        "\nTemperature: \t" + a5_temperature + " degrees Celsius"+
```

```
                                    "\nWindSpeed: \t" + d1_windSpeed + " m/s
                                        " + "\n");
        }

        private static float toInputVoltage(int output){
                return 5.f*(output - 32768)/32768.f;
        }

        private static float toInputFrequency(int output){
                return (float)(CLOCK_FREQUENCY*DIVISION_FACTOR)/output;
        }
}
```

D. Measurement Data

```
1;main_hall;13/1;17:18:3;17.72588;false;true;;;;;false;false
1;room1;13/1;17:18:3;20.07878;false;false;;;;;true;false
1;room2;13/1;17:18:3;21.49052;false;false;;;;;true;false
1;room3;13/1;17:18:3;18.98076;false;false;;;;;true;false
1;room4;13/1;17:18:3;15.52984;false;false;;;;;true;false
1;room5;13/1;17:18:3;14.58868;false;false;;;;;true;false
1;room6;13/1;17:18:3;14.43182;false;false;;;;;true;false
1;room7;13/1;17:18:3;15.21612;false;false;;;;;true;false
1;wc;13/1;17:18:3;;;;;;;;;
1;OutSide;13/1;17:18:3;;;;-0.002897232;4.86084;331.94644;1.7128235;;
2;main_hall;13/1;17:23:25;17.56902;false;false;;;;;false;false
2;room1;13/1;17:23:25;20.07878;false;false;;;;;true;false
2;room2;13/1;17:23:25;21.01994;false;false;;;;;true;false
2;room3;13/1;17:23:25;18.98076;false;false;;;;;true;false
2;room4;13/1;17:23:25;15.52984;false;false;;;;;true;false
2;room5;13/1;17:23:25;14.58868;false;false;;;;;true;false
2;room6;13/1;17:23:25;14.43182;false;false;;;;;true;false
2;room7;13/1;17:23:25;15.21612;false;false;;;;;true;false
2;wc;13/1;17:23:25;;;;;;;;;
2;OutSide;13/1;17:23:25;;;;-0.002897232;4.906616;313.27676;1.5461644;;
3;main_hall;13/1;17:28:2;17.56902;false;false;;;;;false;false
3;room1;13/1;17:28:2;20.07878;false;false;;;;;true;false
3;room2;13/1;17:28:2;21.01994;false;false;;;;;true;false
3;room3;13/1;17:28:2;18.8239;false;false;;;;;true;false
3;room4;13/1;17:28:2;15.52984;false;false;;;;;true;false
3;room5;13/1;17:28:2;14.43182;false;false;;;;;true;false
3;room6;13/1;17:28:2;14.27496;false;false;;;;;true;false
3;room7;13/1;17:28:2;15.05926;false;false;;;;;true;false
3;wc;13/1;17:28:2;;;;;;;;;
3;OutSide;13/1;17:28:2;;;;-0.002897232;4.937134;337.16733;1.9920729;;
4;main_hall;13/1;17:33:9;17.56902;false;false;;;;;false;false
4;room1;13/1;17:33:9;19.6082;false;false;;;;;true;false
4;room2;13/1;17:33:9;21.01994;false;false;;;;;true;false
4;room3;13/1;17:33:9;18.8239;false;false;;;;;true;false
4;room4;13/1;17:33:9;15.52984;false;false;;;;;true;false
4;room5;13/1;17:33:9;14.43182;false;false;;;;;true;false
4;room6;13/1;17:33:9;14.27496;false;false;;;;;true;false
```

```
4;room7;13/1;17:33:9;15.05926;false;false;;;;;true;false
4;wc;13/1;17:33:9;;;;;;;;;
4;OutSide;13/1;17:33:9;;;;-0.002897232;4.921875;320.93643;1.8657082;;
5;main_hall;13/1;17:38:8;17.2553;false;false;;;;;false;false
5;room1;13/1;17:38:8;19.6082;false;false;;;;;true;false
5;room2;13/1;17:38:8;20.70622;false;false;;;;;true;false
5;room3;13/1;17:38:8;18.51018;false;false;;;;;true;false
5;room4;13/1;17:38:8;15.52984;false;false;;;;;true;false
5;room5;13/1;17:38:8;14.43182;false;false;;;;;true;false
5;room6;13/1;17:38:8;14.1181;false;false;;;;;true;false
5;room7;13/1;17:38:8;14.9024;false;false;;;;;true;false
5;wc;13/1;17:38:8;;;;;;;;;
5;OutSide;13/1;17:38:8;;;;-0.002897232;4.8150635;355.89624;1.6138344;;
6;main_hall;13/1;17:43:7;17.2553;false;true;;;;;false;false
6;room1;13/1;17:43:7;19.6082;false;false;;;;;true;false
6;room2;13/1;17:43:7;20.70622;false;false;;;;;true;false
6;room3;13/1;17:43:7;18.51018;false;false;;;;;true;false
6;room4;13/1;17:43:7;15.52984;false;false;;;;;true;false
6;room5;13/1;17:43:7;14.43182;false;false;;;;;true;false
6;room6;13/1;17:43:7;14.1181;false;false;;;;;true;false
6;room7;13/1;17:43:7;14.9024;false;false;;;;;true;false
6;wc;13/1;17:43:7;;;;;;;;;
6;OutSide;13/1;17:43:7;;;;-0.002897232;4.906616;352.7116;2.0895333;;
7;main_hall;13/1;17:48:42;17.2553;false;true;;;;;false;false
7;room1;13/1;17:48:42;19.13762;false;false;;;;;true;false
7;room2;13/1;17:48:42;20.23564;false;false;;;;;true;false
7;room3;13/1;17:48:42;18.51018;false;false;;;;;true;false
7;room4;13/1;17:48:42;15.52984;false;false;;;;;true;false
7;room5;13/1;17:48:42;14.43182;false;false;;;;;true;false
7;room6;13/1;17:48:42;14.1181;false;false;;;;;true;false
7;room7;13/1;17:48:42;14.9024;false;false;;;;;true;false
7;wc;13/1;17:48:42;;;;;;;;;
7;OutSide;13/1;17:48:42;;;;-0.002897232;5.0439453;309.2279;1.5156375;;
8;main_hall;13/1;17:52:49;17.09844;false;true;;;;;false;false
8;room1;13/1;17:52:49;19.13762;false;false;;;;;true;false
8;room2;13/1;17:52:49;20.23564;false;false;;;;;true;false
8;room3;13/1;17:52:49;18.35332;false;false;;;;;true;false
8;room4;13/1;17:52:49;15.52984;false;false;;;;;true;false
8;room5;13/1;17:52:49;14.27496;false;false;;;;;true;false
8;room6;13/1;17:52:49;13.96124;false;false;;;;;true;false
8;room7;13/1;17:52:49;14.9024;false;false;;;;;true;false
8;wc;13/1;17:52:49;;;;;;;;;
8;OutSide;13/1;17:52:49;;;;-0.002897232;5.0286865;355.88437;2.372414;;


...
```

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